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Optimization of a Surface Wire Electrical Grounding System for Tactical Operations

by
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A new surface wire grounding system was developed by the Human Engineering Laboratory (HEL) of Aberdeen Proving Grounds to replace the single, 6-ft, driven rod now in service for grounding tactical systems. The new system consists of a wire placed around the periphery of the vehicle to be grounded. The wire is held in place with a number of relatively short electrodes driven into the earth. The U.S. Army Construction Engineering Research Laboratory (USACERL) was asked by the Army Development and Employment Agency (ADEA) to optimize a number of parameters associated with the new system before fielding it. The main parameters considered by USACERL in this study were electrode design, wire rope characteristics, and takeup reel design. Theoretical and experimental studies indicated that an increase in surface area of an individual earth electrode lowers its resistance to earth. The practical result of this phenomenon is that it is possible to decrease the number of electrodes while maintaining the same total resistance to earth. USACERL provided ADEA with drawings and two prototype systems with a reduced number of redesigned electrodes and a modified takeup reel for field testing.

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A new surface wire grounding system was developed by the Human Engineering Laboratory (HEL) of Aberdeen Proving Grounds to replace the single, 6-ft, driven rod now in service for grounding tactical systems. The new system consists of a wire placed around the periphery of the vehicle to be grounded. The wire is held in place with a number of relatively short electrodes driven into the earth. The U.S. Army Construction Engineering Research Laboratory (USACERL) was asked by the Army Development and Employment Agency (ADEA) to optimize a number of parameters associated with the new system before fielding it. The main parameters considered by USACERL in this study were electrode design, wire rope characteristics, and takeup reel design. Theoretical and experimental studies indicated that an increase in surface area of an individual earth electrode lowers its resistance to earth. The practical result of this phenomenon is that it is possible to decrease the number of electrodes while maintaining the same total resistance to earth. USACERL provided ADEA with drawings and two prototype systems with a reduced number of redesigned electrodes and a modified takeup reel for field testing.

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FOREWORD

This work was performed for the Army Development and Employment Agency (ADEA) at Fort Lewis under Reimbursable Order No. BY7001, dated December 1986. The technical monitor was MAJ Wade Cuthbertson, ADEA Special Projects Officer, MODE-C3I-C2S2. The current ADEA Special Projects Officer is MAJ G. Olafson.

The work was done by the Engineering and Materials Division (EM) of the U.S. Army Construction Engineering Research Laboratory (USACERL). Dr. R. Quattrone is Chief, USACERL-EM. The technical editor was Jane Andrew, USACERL Information Management Office.

The authors express their gratitude to Robert Neathammer, USACERL, for statistical analysis of data in this report and to James Wilcoski, USACERL, for a structural analysis of a variety of cross-sectional shapes.

COL Carl O. Magnell is Commander and Director of USACERL, and Dr. L. R. Shaffer is Technical Director.

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OPTIMIZATION OF A SURFACE WIRE ELECTRICAL GROUNDING SYSTEM FOR TACTICAL OPERATIONS

1 INTRODUCTION

Background

The Army's current communications equipment and other field systems rely heavily on solid state technology. This technology is much more vulnerable to damage and operational upset from high electrical currents, such as those from lightning, than earlier electron tubes were. The magnitude and duration of the current and voltage transients needed to overload these sophisticated systems are much less. When this equipment is mobilized in vehicles during tactical maneuvers, the vehicles must be grounded to protect the equipment from electrical disturbances. A low resistance path to earth ground is desirable; it allows the possibly interfering currents to bypass the sensitive circuitry, minimizes unwanted transient potentials, and prevents damage. Such a path to ground would also reduce noise in signal and control circuits and provide a sink for static charge, thus improving the functioning of instruments and communications equipment. Aside from the hardware, the safety of persons in and around the vehicles is, of course, also a concern.

An effective tactical grounding system for such vehicles must not only provide adequate electrical protection for both equipment and personnel, but it must also be easy and safe to transport, install, and remove, and it must be relatively inexpensive. Grounding for tactical systems must therefore use the most advanced technology.

The grounding system historically used for tactical shelters consists of a single, 6-ft-long, 3/4-in.-diameter,* cylindrical rod which is driven into the earth with a sledgehammer. This rod is connected to the shelter by a cable. Installing such a grounding system is a labor-intensive and time-consuming process requiring the efforts of two persons--one who holds the rod and the other who wields the sledgehammer to drive the rod into the earth. Penetrating the earth to a 6-ft depth often is difficult or impossible due to rocks or other hard formations below the surface. In addition, the installation process may be dangerous to personnel. At the end of the maneuver, extracting the rod is at least as difficult as emplacing it, so that many times the rod is abandoned. As a result, the average expected lifetime for 6-ft ground electrodes is approximately three uses.

An alternative system for grounding that addresses the problems related to a single-electrode system for tactical applications has been designed and tested by the Human Engineering Laboratory (HEL) of Aberdeen Proving Grounds. It consists of 26 short grounding stakes or electrodes (9 in. long) strung along a surface wire which is placed around and relatively close (3 to 6 ft) to the vehicle being protected. Figure 1 shows the system concept. HEL's system used 100 ft of 1/8-in. stainless steel wire rope (aircraft cable) as the surface wire. The electrodes were cylindrical, 9/16-in.-diameter pegs with a cross bar welded to the top. With the 100 ft length of wire rope and 26 electrodes, the electrode spacing is about one pace. The electrode length was about 9 in. The cable winder for the HEL prototype was a modified boat trailer reel.

ADEA produced a number of the HEL prototypes for field evaluation. Users involved in the evaluation were unanimous in preferring the HEL system over the 6-ft ground rod. However, they found that the large number of electrodes was an inconvenience of another sort. Also, the takeup reel

*1 ft = 0.3048 m; 1 in. = 25.4 mm.

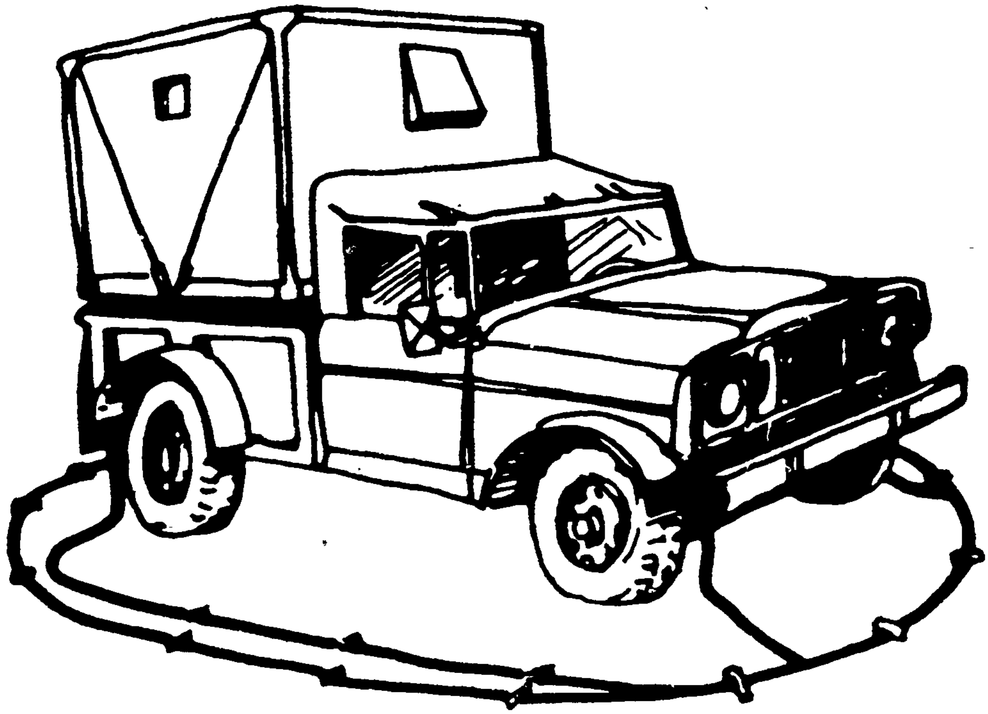

Figure 1. Surface wire grounding system installed around a tactical vehicle.

was inconvenient to handle and excessively noisy. Overall, it seemed this concept had excellent potential for fielding, but improvements on the design appeared to be possible. Upon learning of USACERL's facilities and previous work in electromagnetic protection, ADEA tasked USACERL to identify and develop improvements for the new system. The questions raised were related to the number of electrodes, the length of surface wire, the reel design, and the materials used.

Objective

The objective of this research was to determine theoretically and experimentally the optimal design for certain parameters of the surface wire electrical grounding system invented by HEL. The parameters of interest were (1) the effectiveness of the electrical connection to the earth and (2) the ease of installation and retrieval.

Scope

This study examined alternatives for the following:

- Material, shape, length, method of fabrication, and number of electrodes.
- Material, length, and diameter of the surface wire.
- Design of the takeup reel.

The surface wire grounding system described in this report has been optimized only for tactical operations in which the system is moved frequently. Other considerations not addressed in this study may apply to other applications, particularly for fixed facilities.

Mode of Technology Transfer

USACERL has provided the Army Development and Employment Agency (ADEA) and the U.S. Army Natick Research, Development, and Evaluation (RD&E) Center with prototype surface wire ground systems and related detailed drawings incorporating the features developed during this study. ADEA has since remanded the system to the Army Materiel Command's (AMC) Communications Electronics Command (CECOM) for fielding in place of the standard ground rod. CECOM has submitted the system for type certification. Natick RD&E Center will use the drawings as part of the contract documentation for an initial procurement of 800 units for the Standardized Integrated Command Post (a field relocatable system).

2 THEORETICAL CONSIDERATIONS

The resistance between an electrode and the earth depends on three values: (1) resistance of the metal electrode; (2) contact resistance between the electrode and the soil surrounding it, and (3) resistance of the soil from the electrode surface outward. The first resistance should be negligible, and usually the second, "contact resistance," is so small (a fraction of an ohm) that it can be ignored.[1] However, in the case of the 6-ft tactical ground rod, the contact resistance can be affected by the vibration of the rod as it is driven into the ground. This vibration typically enlarges the sides of the upper portion of the hole where the rod penetrates. This condition can substantially decrease the total surface area of the rod in contact with the earth. When the entire rod is driven in, it is possible that only its bottom portion is in good contact with the earth. This problem is unique to temporary tactical systems; with permanent installation the soil would gradually work its way back to the electrode and decrease its resistance to the earth. Such a lack of good surface contact can increase the overall resistance of the ground system, but more importantly it can create a dangerous difference in potential between the rod and the surface of the earth--a possible significant personnel hazard.

Personnel hazards related to grounding include those associated with "step potential" and "touch potential." Step potential is simply the difference in voltage which can occur between two points on the ground separated by the distance of a person's stride (approximately 3 ft). Step potential may be a threat to people in the immediate area of a single grounding electrode while current is dissipating from a lightning stroke. The largest current is concentrated in the vicinity of the rod. Lightning currents, which can be several thousand amperes in amplitude, passing through as little as 1 ohm resistance in a radial foot of earth, for example, can create a dangerously high step potential for a person walking in the area.

This hazard can be reduced with a "distributed" ground electrode system, where the dissipating current is divided in parallel into a number of branches, or ground rods located in the immediate perimeter of a tactical unit. This multiple-rod configuration increases the effective size of the grounding system. The dissipating current, rather than being concentrated near a single electrode, is distributed over a much greater area. This substantially reduces any step potential for nearby persons.

Touch potential as it applies to this discussion is the voltage difference between the tactical vehicle chassis and the ground just below it. The touch potential becomes a hazard when a person, standing on the ground, is in contact with the vehicle when a lightning stroke or power fault occurs. This hazard can only be minimized with a good grounding system which will give the electric current a path of low resistance to ground.

A theoretical justification for considering a multiple electrode system as an alternative to a single electrode can be developed from the basic resistance to earth equations.

This equation[2] describes the resistance of a single cylindrical rod driven vertically in the earth:

$$R = \frac{\rho}{2\pi L} \quad \ln\left(\frac{4L}{r}\right) - 1 \qquad \text{[Eq 1]}$$

[1]*Recommended Practices for Grounding of Industrial and Commercial Power Systems*, Institute of Electrical and Electronics Engineers (IEEE) Standard 142-1982.

[2]H. B. Dwight, "Calculation of Resistance to Ground," *Electrical Engineering*, Vol 55 (December 1936), pp 1319-1328.

where ρ = resistivity of the soil
L = rod length in contact with soil
r = rod radius.

Equation 2 gives the resistance of a long line of N straight cylindrical electrodes of equal length connected by cable at the tops.[3] The resulting resistance is somewhat greater than 1/N times the resistance of a single isolated rod:

$$R = \frac{1}{N} \frac{\rho}{2\pi L} \ln \frac{4L}{r} - 1 + \frac{2L}{s} \ln \frac{2N}{\pi} \qquad \text{[Eq 2]}$$

where N = number of rods
ρ = resistivity of the soil
L = rod length in contact with soil
r = rod radius
s = equidistant spacing between rods in line.

These resistance formulas have been derived from a more general formula, Equation 3:[4]

$$R = \rho \frac{\ell}{A} \qquad \text{[Eq 3]}$$

where ρ = resistivity of the soil
ℓ = length of conducting path
A = cross-sectional area of conducting path.

The above equations indicate that increasing the surface area in contact with the soil while maintaining the length of an electrode will result in a decrease in resistance to ground.

The resistance of an electrode to earth at a particular location can be viewed as the sum of the resistance of a series of "shells" of earth located progressively farther away from the electrode. Each shell has the same thickness, a linear dimension measured outward from the electrode. The incremental resistance in the direction of current flow is highest in the shell of earth immediately surrounding the electrode since its surface area is the smallest. Successive shells have larger areas and progressively smaller associated resistances. This means that with a uniform earth "the lowest earth resistance is obtained with electrode configurations which have largest areas in contact with the earth."[5] This also means that the soil nearest the electrode is the most important in determining the resistance to earth, and that good contact is necessary for a minimum resistance value.

The cylinder geometry gives a minimum surface area for a particular volume of material for an elongated shape. Historically, driven electrodes used for grounding systems have been cylinders (rods). These are readily available in a variety of diameters and materials. However, any other shape containing the same volume will have a greater surface area available for contact with the soil.

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[3]Military Handbook 419, "Grounding, Bonding and Shielding for Electronic Equipments and Facilities" (21 January 1982), p 2-27 (equation 2-25).
[4]Military Handbook 419, p 2-7 (equation 2-1).
[5]Military Handbook 419, p 2-19 (equation 2-19).

3 ELECTRODE DESIGN

Several electrode designs were considered as candidates for replacing the T-shaped, cylindrical electrodes of the HEL system. Two sets of theoretical calcuations were done, using Equation 2. The first examined the effect of electrode length on resistance to ground; the second examined the effect of increasing the surface area of the electrodes. Both sets of calculations were for multiple electrode systems with varying numbers of electrodes. The results of these calculations are presented in Figures 2 and 3. Equation 2 is derived for cylindrical electrodes and does not appear to be readily modified to account for changes in surface area resulting from different shapes. Thus the calculations were done by increasing the diameter to a value that would produce the desired increase in surface area. Any error introduced by this approximation should be insignificant. In addition, it should be noted that the equation calculates the resistance to earth for multiple electrodes in a straight line, not in a circle.

Based on these calculations and the fact that from a user will feel that "fewer is better," USACERL's proposed design consists of 15 to 18 electrodes, each 10 to 12 in. long with a cross-sectional shape that results in a surface area of two times that of a 9/16-in. diameter cylinder.

A number of experimental electrode designs were tested. The straight cylinder electrode was a reference to which the performance of the other proposed designs was compared. Every design examined, except for the cylinder, included some tapering of the stake from top to bottom. Tapering should result in a degree of compaction of the soil against the stake as it is driven, giving better surface contact between the soil and the electrode, minimizing the vibration-related soil compaction problem discussed earlier. In addition to having adequate tapering, any new electrode design should remain within or near certain volume (weight) limits (based on a straight cylinder) and have a maximum surface area, while retaining most of the structural strength of the cylinder. Another goal for any new design was an equivalent or lighter total weight of the electrodes to meet a weight limit of 30 lb for the total system.

Figure 4 shows the different electrode configurations examined in this study. The figure includes the formulas for determining surface areas and volumes of the various shapes.

A tapered cylinder can be expected to have more uniform continuous contact with the soil than the straight cylinder; however, its surface area is equal to that of a straight cylinder with the same volume.

The dimensions of multipoint "star" electrode designs can be changed in a variety of ways to yield high surface area to volume ratios. Tables 1 and 2 list the results of some calculations of surface areas resulting from varying the dimensions of three- and four-point stars. It can be seen that total surface area of the four-point star is greater than for a three-point star with an equivalent span. Thus the three-point star configuration was not seriously considered for this study, since the overall dimensions of the star would need to be considerably increased to maintain equivalent surface areas.

The calculations on the three- and four-point star cross section shapes indicate that increasing the number of points on the star or vanes on the electrode is a simple technique for increasing the electrode's surface area. However, adding more points or vanes may not necessarily decrease the resistance to earth. Because of the smaller angle between points and the granular nature of many soils, the soil particles may be prevented from making good physical contact with the electrode at the sharp interior angles. For this reason, and due to the difficulty of fabricating test samples with more vanes, the four-point star configuration was picked for experimental studies. ADEA placed a constraint on the electrode configuration by specifying a maximum span of 1.25 to 1.375 in. at the top.

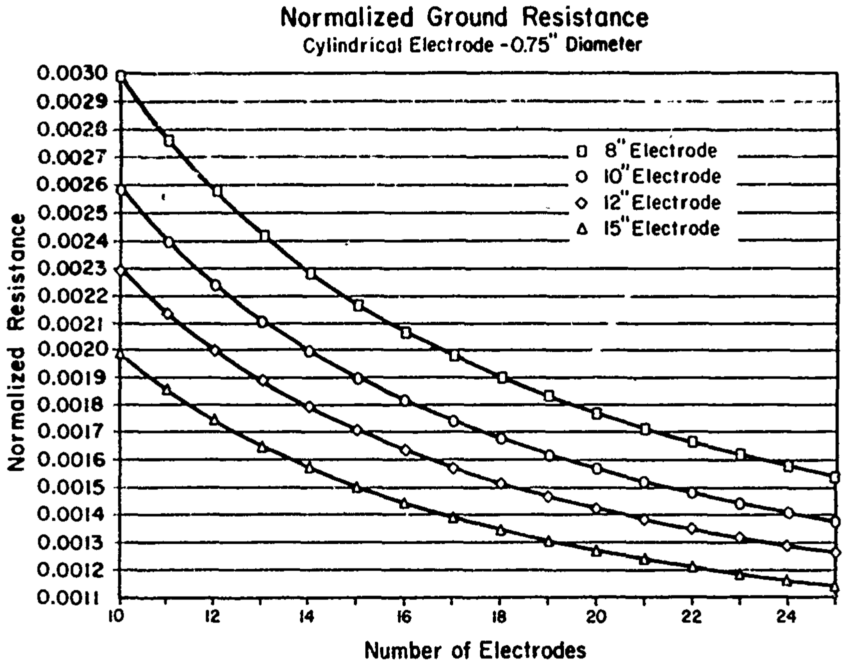


Figure 2. Theoretical calculation of resistance to earth for multiple electrode systems for electrodes of various lengths.

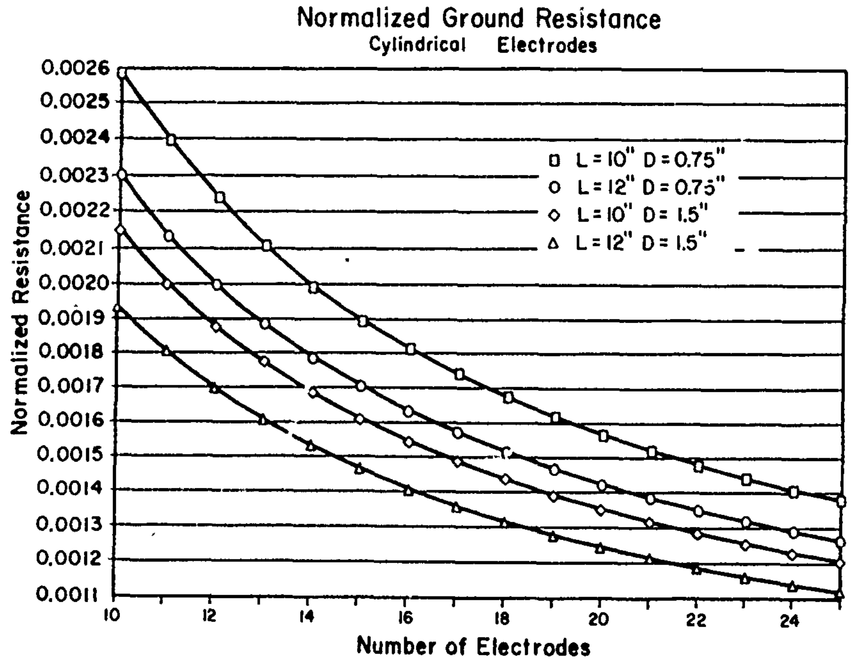
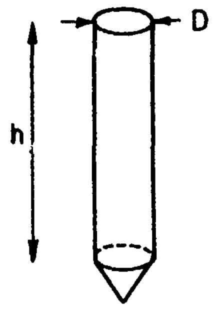


Figure 3. Theoretical calculation of resistance to earth for multiple electrode systems with different diameters and lengths.

Straight cylinder with diameter D, height h (ignoring point):

$$A = \pi D h$$

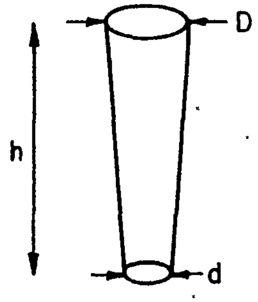
$$V = \pi (D/2)^2 h$$



Tapered cylinder with top diameter D, bottom diameter d, height h:

$$A = \pi \frac{(D + d)}{2} h$$

$$V = \frac{\pi h}{12} (D^2 + Dd - d^2)$$



Cross stake with top width T, bottom width B, plate thickness W, height h:

$$A = 2h(B + T)$$

$$V = hw(B + T)$$

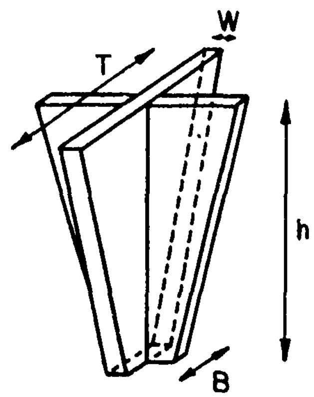
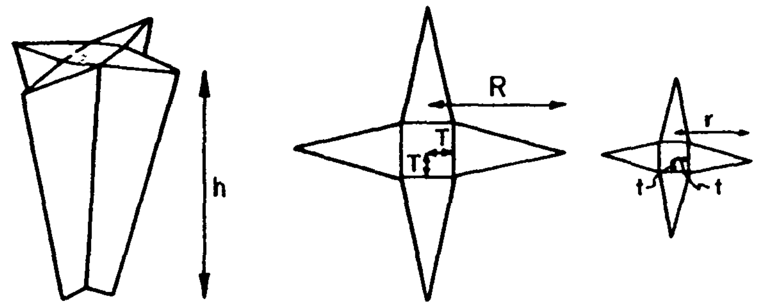


Figure 4. Proposed electrode configurations--surface areas and volumes.

Four-point star (see illustration for dimensions)

$$A = 4h\left[\sqrt{\;^{2} + (r-t)^2} + \sqrt{T^2 + (R - T)^2}\right]$$

$$V = \frac{4}{3}h(RT + \frac{rT}{2} + \frac{Rt}{2} + rt)$$

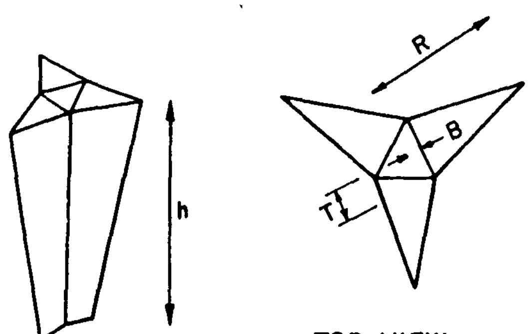


TOP VIEW BOTTOM VIEW

Three-point star (see illustration for dimensions)

$$A = 3h\left[\sqrt{t^2 + (r - b)^2} + \sqrt{T^2 + (R - B)^2}\right]$$

$$V = h\left[\frac{4}{3}(RT + rt) + \frac{2}{3}(rT + Rt) - \frac{1}{3}(bt + BT) - \frac{1}{6}(Bt - bT)\right]$$



TOP VIEW

Figure 4. (Cont'd).

Table 1

Surface Areas of Three Point "Stars" of Various Dimensions

$$\text{Formula } A = 3H\left(\sqrt{[T + T + (R\text{-}T)(R\text{-}T)]} + \sqrt{[t + t + (r\text{-}t)(r\text{-}t)]}\right)$$

T	T tan 30°	R	t	t tan 30°	r	H	Area	Area Ratio
1/4"-1/8" Taper								
0.0625	0.036	0.625	0.625	0.036	0.25	10	24.2	1.4
0.125	0.072	0.625	0.625	0.036	0.25	10	23.2	1.3
0.125	0.072	0.625	0.625	0.036	0.375	10	27.0	1.5
0.125	0.072	0.625	0.625	0.036	0.5	10	30.7	1.7
0.125	0.072	0.6875	0.625	0.036	0.25	10	25.1	1.4
0.125	0.072	0.6875	0.625	0.036	0.375	10	28.8	1.6
0.125	0.072	0.6875	0.625	0.036	0.5	10	32.5	1.8
0.125	0.072	0.75	0.625	0.036	0.25	10	27.0	1.5
0.125	0.072	0.75	0.625	0.036	0.375	10	30.7	1.7
0.125	0.072	0.75	0.625	0.036	0.5	10	34.4	1.9
No Taper (1/8")								
0.625	0.036	0.0625	0.625	0.036	0.25	10	24.2	1.4
0.625	0.036	0.0625	0.625	0.036	0.375	10	27.9	1.6
0.625	0.036	0.0625	0.625	0.036	0.5	10	31.7	1.8
0.625	0.036	0.6875	0.625	0.036	0.25	10	26.1	1.5
0.625	0.036	0.6875	0.625	0.036	0.375	10	29.8	1.7
0.625	0.036	0.6875	0.625	0.036	0.5	10	33.5	1.9
0.625	0.036	0.75	0.625	0.036	0.25	10	28.0	1.6
0.625	0.036	0.75	0.625	0.036	0.375	10	31.7	1.8
0.625	0.036	0.75	0.625	0.036	0.5	10	35.4	2.0
1/8"-1/16" Taper								
0.625	0.036	0.0625	0.031	0.018	0.25	10	24.7	1.4
0.625	0.036	0.0625	0.031	0.018	0.375	10	28.4	1.6
0.625	0.036	0.6875	0.031	0.018	0.5	10	32.2	1.8
0.625	0.036	0.6875	0.031	0.018	0.25	10	26.6	1.5
0.625	0.036	0.6875	0.031	0.018	0.375	10	30.3	1.7
0.625	0.036	0.6875	0.031	0.018	0.5	10	34.0	1.9
0.625	0.036	0.75	0.031	0.018	0.25	10	28.4	1.6
0.625	0.036	0.75	0.031	0.018	0.375	10	32.2	1.8
0.625	0.036	0.75	0.031	0.018	0.5	10	35.9	2.0
3/16"-1/4" Taper								
0.09375	0.054	0.625	0.0625	0.036	0.25	10	23.7	1.3
0.09375	0.054	0.625	0.0625	0.036	0.375	10	27.4	1.5
0.09375	0.054	0.625	0.0625	0.036	0.5	10	31.2	1.8
0.09375	0.054	0.6875	0.0625	0.036	0.25	10	25.6	1.4
0.09375	0.054	0.6875	0.0625	0.036	0.375	10	29.3	1.6
0.09375	0.054	0.6875	0.0625	0.036	0.5	10	33.0	1.9
0.09375	0.054	0.75	0.0625	0.036	0.25	10	27.4	1.5
0.09375	0.054	0.75	0.0625	0.036	0.375	10	31.2	1.8
0.09375	0.054	0.75	0.0625	0.036	0.5	10	34.9	2.0

Table 2

Surface Areas of Four Point "Stars" of Various Dimensions

Formula $A = 4H\left(\sqrt{[T + T + (R-T)(R-T)]} + \sqrt{[t + t + (r-t)(r-t)]}\right)$

T	R	t	r	H	Area	Area Ratio
1/4"-1/8" Taper						
0.125	0.625	0.0625	0.25	10	28.5	1.6
0.125	0.625	0.0625	0.375	10	33.4	1.9
0.125	0.625	0.0625	0.5	10	38.3	2.2
0.125	0.6875	0.0625	0.25	10	31.0	1.7
0.125	0.6875	0.0625	0.375	10	35.8	2.0
0.125	0.6875	0.0625	0.5	10	40.7	2.3
0.125	0.75	0.0625	0.25	10	33.4	1.9
0.125	0.75	0.0625	0.375	10	38.2	2.2
0.125	0.75	0.0625	0.5	10	43.2	2.4
No Taper (1/8")						
0.0625	0.625	0.0625	0.25	10	30.5	1.7
0.0625	0.625	0.0625	0.375	10	35.4	2.0
0.0625	0.625	0.0625	0.5	10	40.3	2.3
0.0625	0.6875	0.0625	0.25	10	33.0	1.9
0.0625	0.6875	0.0625	0.375	10	37.9	2.1
0.0625	0.6875	0.0625	0.5	10	42.8	2.4
0.0625	0.75	0.0625	0.25	10	35.5	2.0
0.0625	0.75	0.0625	0.375	10	40.4	2.3
0.0625	0.75	0.0625	0.5	10	45.3	2.6
1/8"-1/16" Taper						
0.0625	0.625	0.031	0.25	10	31.5	1.8
0.0625	0.625	0.031	0.375	10	36.5	2.1
0.0625	0.625	0.031	0.5	10	41.4	2.3
0.0625	0.6875	0.031	0.25	10	34.0	1.9
0.0625	0.6875	0.031	0.375	10	38.9	2.2
0.0625	0.6875	0.031	0.5	10	43.9	2.5
0.0625	0.75	0.031	0.25	10	36.5	2.1
0.0625	0.75	0.031	0.375	10	41.4	2.3
0.0625	0.75	0.031	0.5	10	46.4	2.6
3/16"-1/4" Taper						
0.09375	0.625	0.0625	0.25	10	29.5	1.7
0.09375	0.625	0.0625	0.375	10	34.3	1.9
0.09375	0.625	0.0625	0.5	10	39.6	2.2
0.09375	0.6875	0.0625	0.25	10	31.9	1.8
0.09375	0.6875	0.0625	0.375	10	36.8	2.1
0.09375	0.6875	0.0625	0.5	10	41.7	2.3
0.09375	0.75	0.0625	0.25	10	34.4	1.9
0.09375	0.75	0.0625	0.375	10	39.3	2.2
0.09375	0.75	0.0625	0.5	10	44.2	2.5

The bending strength of a longitudinal structure is proportional to the radius of the transverse cross section of that structure at the location which the bending stress is applied. This indicates that any configuration other than a cylinder will be weaker in bending stress than the cylinder (assuming there is an equal volume of material in the total structure.) A structural analysis of a cross shape is given in the Appendix.

USACERL fabricated and tested the resistance to earth of electrodes of various shapes and dimensions, including straight cylinders, tapered cylinders, and a variety of tapered cross-shaped electrodes. Their dimensions are listed in Table 3. A version of the HEL system, consisting of twenty-six 9-in. cylindrical electrodes on 100 ft of stainless steel (1/8-in. diameter, 7 by 19) wire rope, was given to USACERL at the beginning of the study for comparison with CERL designs. USA-CERL researchers made a system with 15 cross-shaped electrodes constructed of 1/8 in. steel plate, as shown in Figure 5 with 70 ft of 1/8-in. stainless-steel wire rope. This system was built to evaluate the effects of increased electrode surface area in a multielectrode system. It should be noted that the vanes of the electrodes of this system were not tapered and the electrodes were not galvanized. Sixty specially-shaped cast electrodes of a design incorporating the theoretically and experimentally desirable features determined in this study were procured for testing and were used as a part of the systems passed to ADEA for evaluation before recommended fielding. A version of this system is also shown in Figure 5, along with a number of other electrode shapes and sizes that were tested.

The material used for the cast electrodes was leaded red brass, Cu-5%Sn-5%Pb-5%Zn. The fabrication process is termed "molding in green sand." The contractor did not have the in-house capability to work with higher melting point metals but was able to obtain a number of Type 25-12 stainless steel electrodes from a larger local casting firm. They were procured after most of the emperical studies had been completed and were not tested side-by-side with the others. They appear to be considerably stronger than the brass. Stainless steel electrodes would be electrochemically compatible with stainless-steel wire rope (see Chapter 6), but the material cost is probably twice that of the brass.

Table 3

Electrode Designs Constructed and Tested by USACERL

Design	Length, in.	Diameter (or diagonal), in. Top	Bottom
Cylinder	8	0.75	0.75
Cylinder	15	0.75	0.75
Cylinder	8	0.5625	0.5625 (9/16)
Cylinder	15	0.5625	0.5625
Tapered Cylinder	8	1.25	0.25
Tapered Cylinder	15	1.25	0.25
Cross Stake	8	1.25	0.05
Cross Stake	15	1.25	0.05
Cross Stake	8	1.5	0.05
Cross Stake	15	1.5	0.05

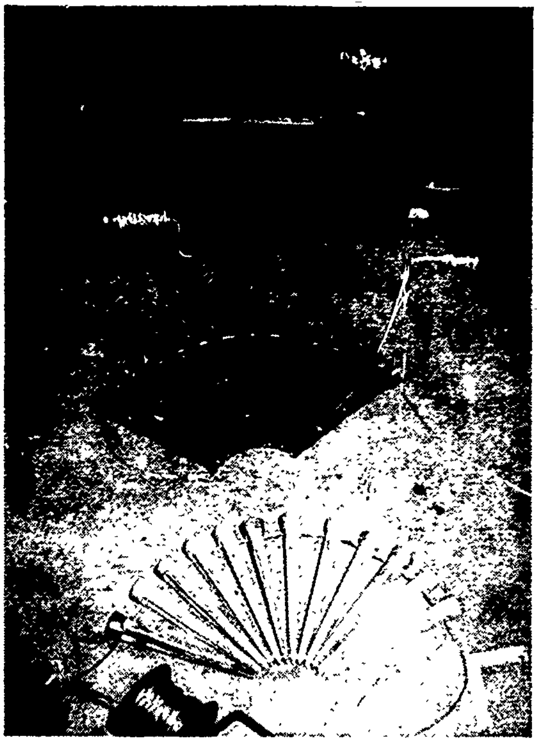


Figure 5. Experimental multiple electrode surface wire grounding systems.

4 EXPERIMENTAL PROCEDURE AND ANALYSIS

Two types of grounding tests were performed, one to measure the resistance to earth of individual electrodes and the other to test the entire surface wire, multiple electrode systems. The methods for performing these tests are described in the instruction manual for the ground resistance measurement device used.[6]

Both tests were conducted according to the standard "three point" or "fall of potential" method for measuring the resistance of a grounding system.[7]

To understand the idea of earth ground resistance testing, consider the schematic in Figure 6. In very general terms, the test consists of sending a known current I from point E (electrode under test) to point C (current element probe), and measuring the voltage V from point E to point P (potential element probe, located between E and C). Resistance is then determined by the measured voltage V divided by known current I. The measurement apparatus used for this test is contained within one instrument, the battery-operated Megger Earth Tester (Model #250241). This instrument is used with insulated cables extending to the 17-in. long, 1/2-in. diameter test probes driven into the ground at points P and C, and to the electrode under test located at point E. Only one reading is needed using this instrument. The electrodes are placed and connected to the meter, then the reading is taken.

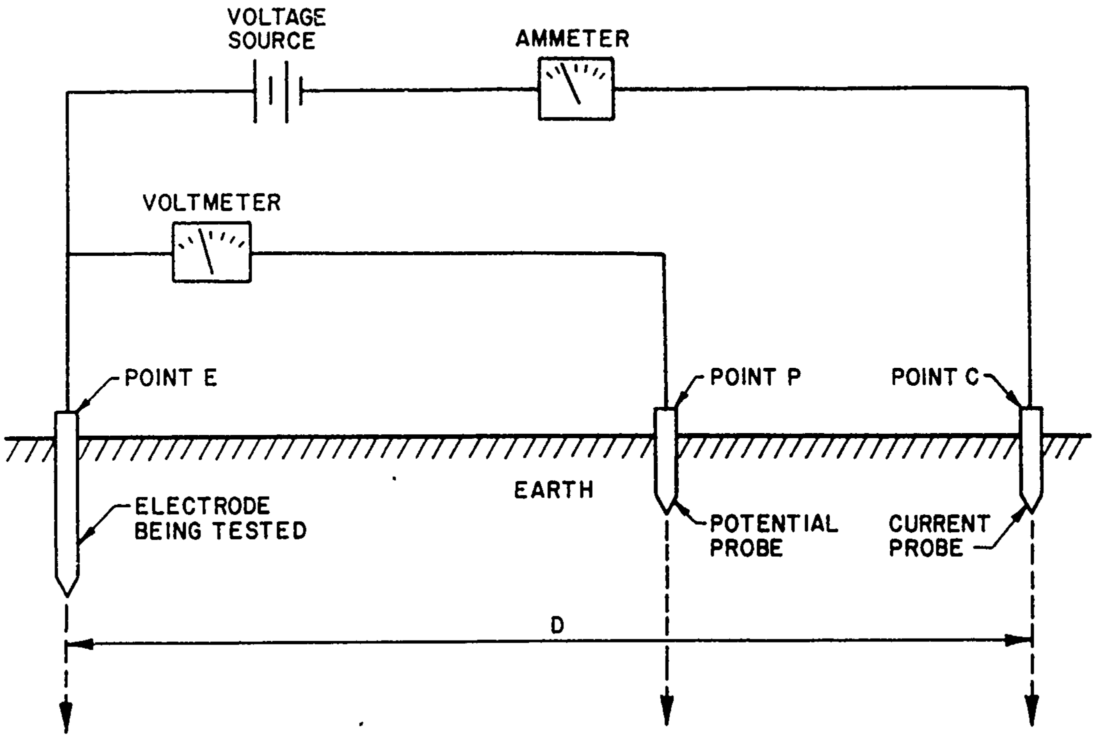


Figure 6. Measurement of resistance to earth for a ground electrode using "fall of potential" method.

[6] *Instruction Manual 25-J-36: Megger Earth Testers (Null Balance)* (Biddle Instruments, Blue Bell, PA, May 1986).
[7] Military Handbook 419, p 2-35.

The location of point P must be far enough away from the electrode at E that the rate of increase of resistance as a function of distance from the electrode becomes almost a constant. That is, the incremental earth "shells" between points P and E have such a great surface area that they add little to the total resistance (see Equation 3). However, point P, the potential probe, must also be at a great enough distance from point C, the current probe, such that the resistance values measured are not influenced significantly by the earth "shells" around the test probe at point C. Generally, the correct resistance is found if the probe at P is placed at 62 percent of the distance from point E to C (with P nearer to C) (see Figure 7).[8]

For testing single electrodes it is recommended that point C be 100 ft away from the electrode, with point P located between C and the electrode under test at 62 ft from the electrode. For testing a multiple electrode system, the distance from the electrical center of the grounding system to point C should be at least five times the largest dimension or diagonal of the ground system area. Point P then is located at 62 percent of this distance from the electrical center of the grounding system. Such dimensions should yield a value of earth ground resistance with 90 percent accuracy.[9]

For the individual electrode tests conducted for this study, the resistance value was found for point P at 62 ft away from the electrode under test, with point C at 100 ft away from this electrode (see Figure 8).

The multiple electrode system studied was laid out with a diameter of about 19 ft, and a perimeter of 60 ft. (Fifteen or 26 test electrodes of equal length were placed equidistantly around the perimeter of this circle.) Thus the minimum distance from the middle of the circle to point C is five times the diameter, or 95 ft. For better accuracy in the multiple electrode system tests conducted in this study, point C was extended somewhat beyond this minimum to 110 ft from the center of the circle. Point P was located at 62 percent of this distance, or about 68 ft away from the center point, as shown in Figure 9.

The tests were conducted at USACERL on a number of different days with varying moisture conditions. All tests used for direct performance comparison of different electrode designs were conducted on the same day in the same general vicinity; however, not all the tests reported were conducted on the same day. This may limit to some extent the general conclusions which can be drawn from the data, particularly comparisons between the individual electrode data and the multielectrode data.

USACERL is located on relatively low resistance loam which, for most tests, was relatively moist. Extending the analysis to other soil types should be approached with caution.

Individual Electrode Tests

Resistance to ground tests were conducted for a variety of electrodes of different shapes and lengths. The electrodes tested, with their descriptions, are listed below. For any particular test, all electrodes were driven into the ground separately and removed in sequence at essentially the same location and time. Each electrode was placed in a location slightly removed from where the previous electrodes had been placed and all tests in each group were conducted on the same day. Thus variation in soil resistivity should not be a variable.

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[8]Military Handbook 419, p 2-36.
[9]Military Handbook 419, p 2-42.

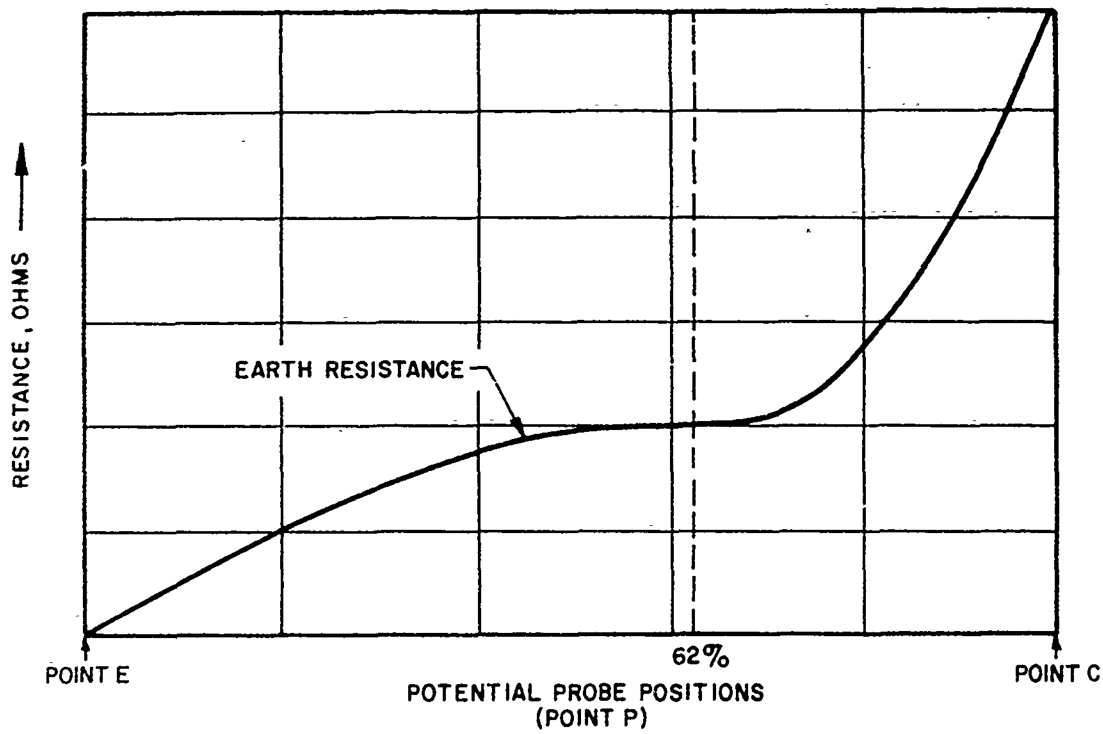


Figure 7. Placement of potential probe for correct resistance to earth value.

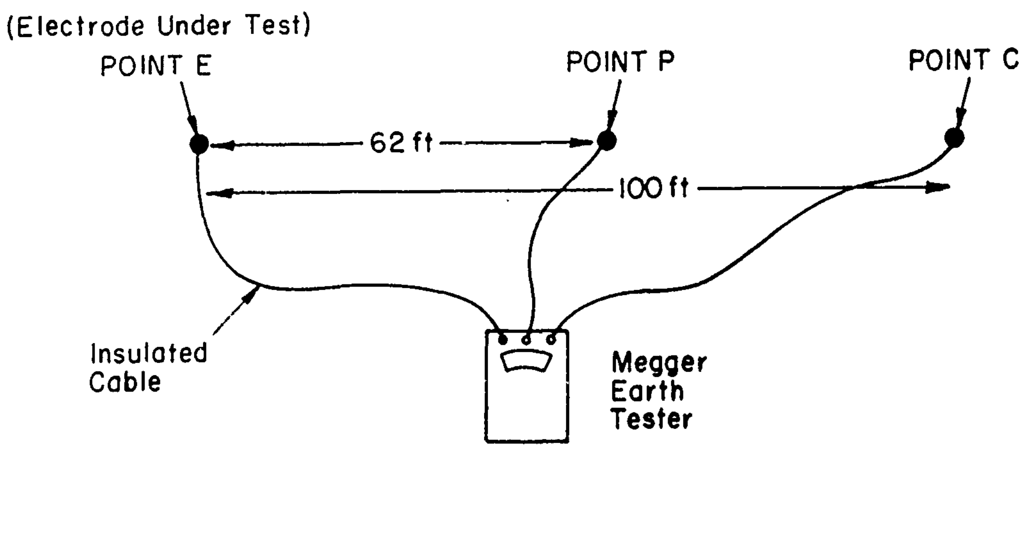


Figure 8. "Sky view" of test configuration for measuring the resistance to earth of individual electrodes.

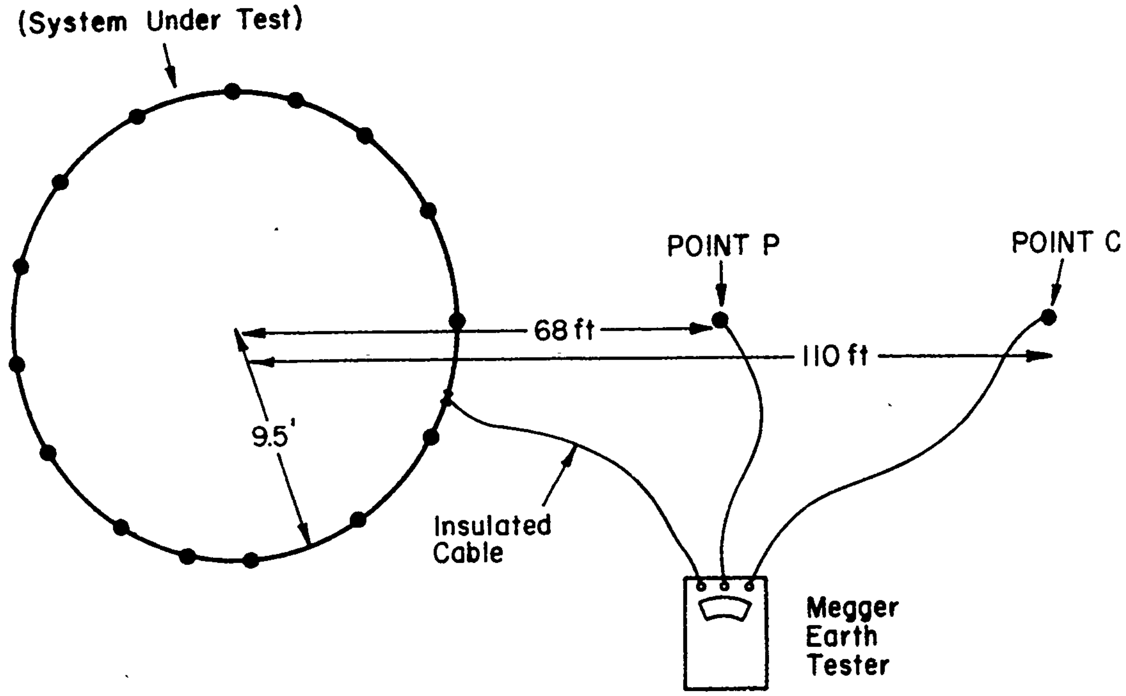


Figure 9. "Sky view" of test configuration for measuring the resistance to earth for multiple electrode systems.

Test Group 1

The first group had three types of electrodes: a straight cylinder, a tapered cylinder, and a cross-shaped design. Each type was made in two lengths, 8 in. and 15 in. The dimensions of interest, corresponding to the variables defined in Figure 4, are shown in Figure 10. The volumes and surface areas of these electrodes, calculated according to the formulas given in Figure 4, are listed in Table 4. In this group, electrodes of the same length had the same volume of metal. Also, the straight cylinder and tapered cylinder models had identical surface areas. The cross-shaped electrode of this group had about 1.5 times as much surface area as the straight cylinder and tapered designs.

The length of electrode was the main variable of interest examined in this group of tests. The effect of length on resistance can be seen by comparing the resistance to earth values obtained for electrodes of the same shape but different lengths. The cylinder and tapered cylinder have the same surface area for equal volume, thus it should be possible to also identify the effect of tapering on overall resistance. The cross-shaped electrode was used to investigate the effects of increased electrode surface area on resistance to earth.

Test Group 2

The second test group consisted of two types of electrodes: the straight cylinder and the cross-shaped stake. These electrodes were also made in 8-in. and 15-in. lengths. Other dimensions, such as diameter and plate thickness, were changed from those of the first group of electrodes. The dimensions of interest are shown in Figure 11. The respective volumes and surface areas of these test samples, as calculated according to previous formulas, are tabulated in Table 5.

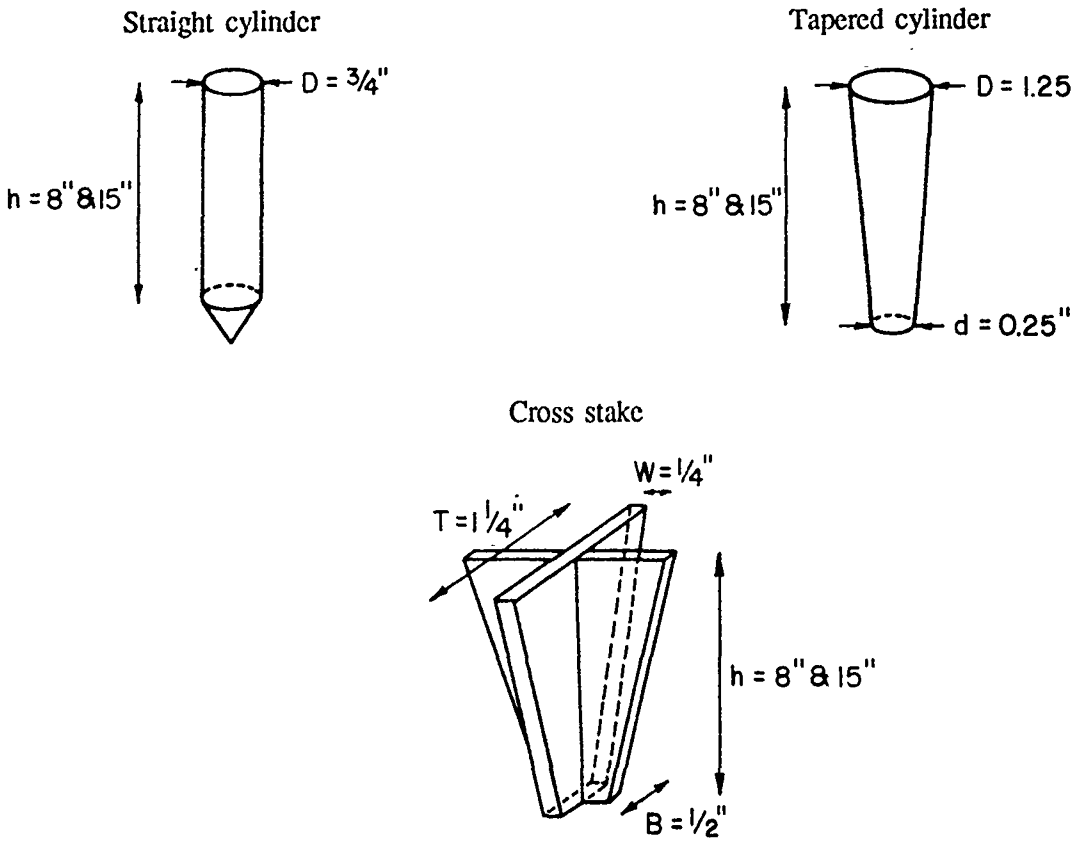
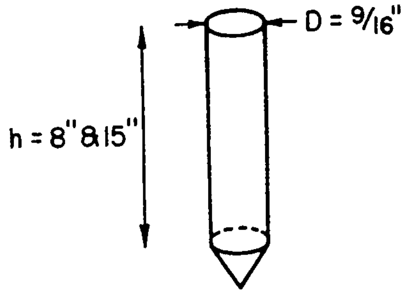


Figure 10. Test group 1 electrodes with dimensions.

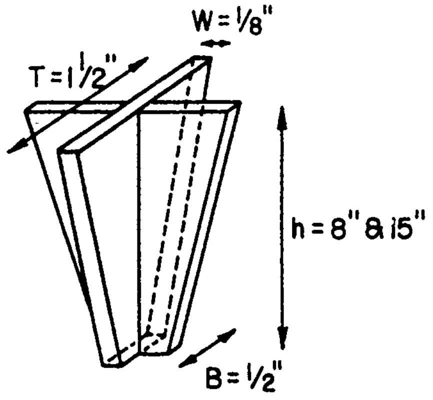
Table 4

Volume and Surface Area for Group 1 Electrodes

	Group 1 Electrode Type	Volume (cu in.)	Surface Area (sq in.)	Area Ratio (to Cylin.)
15 in.	str. cylinder (3/4 in.)	6.63	35.34	1
	tapered cylinder	7.12	35.36	1
	cross stake	6.56	52.50	1.49
8 in.	str. cylinder (3/4 in.)	3.53	18.85	1
	tapered cylinder	3.80	18.89	1
	cross stake	3.50	28.00	1.49



Straight cylinder



Cross stake

Figure 11. Test group 2 electrodes with dimensions.

Table 5

Volume and Surface Area for Group 2 Electrodes

	Group 2 Electrode Type	Volume (cu in.)	Surface Area (sq in.)	Area Ratio (to Cylin.)
15 in.	str. cylinder (9/16 in. dia.)	3.73	26.51	1
	cross stake	3.75	60.00	2.26
8 in.	str. cylinder (9/16 in. dia.)	1.99	14.14	1
	cross stake	2.00	32.00	2.26

Again each set of electrodes of a given length will have about the same volume (these volumes are about 56 percent of those for the electrodes of the same length in Group 1). In this test group, the major difference between each cross-shaped electrode and straight cylinder electrode is that for any length, the cross-shaped stake has about 2.25 times the surface area of the straight cylinder. This test evaluated the effect on resistance to earth of significantly increasing the surface area of ground electrodes.

Test Group 3

The third group of electrodes tested consisted of four different designs all 10 in. long. These were:

1. A specially cast red brass prototype with approximately 2.4 times the surface area of a 9/16-in. diameter c inder.

2. A 9/16-in. diameter cylinder.

3. A 1.5-in. diameter cross.

4. A 1.25-in. diameter cross.

The samples are shown schematically in Figure 12 without the cylindrical tops which were incorporated as a striking surface c the cast and 1.25-in. diameter electrodes. The cast electrode was designed to provide a continuous taper along all surfaces. The 1.5 in. diameter cross-shaped electrode was used as a model for the cast electrode. The 9/16-in. diameter cylinder was basically the electrode design from the system supplied by HEL. The cross designs were fabricated from 1/8-in. flat plate steel and either welded or brazed. The sample dimensions were as shown in Figure 13. The volumes and surface areas of these electrodes are listed in Table 6.

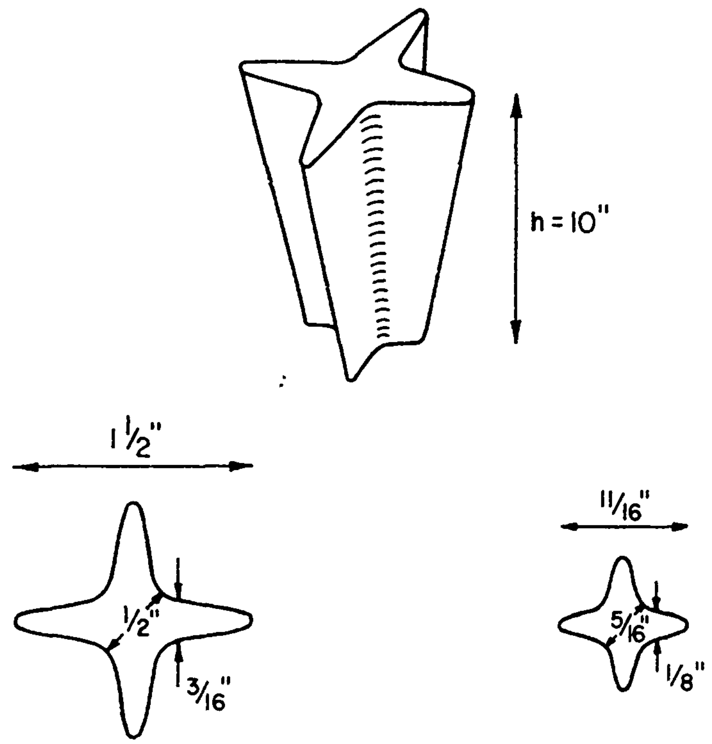
The data from the individual electrode tests are listed in Table 7.

Analysis of Data: Individual Electrodes

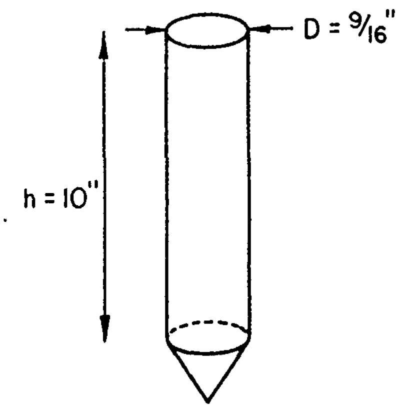
The resistance to earth was measured a number of times for each electrode, three times each for Groups 1 and 2, and ten times for Group 3. The values for each electrode were then averaged for analysis.

The Group 1 test results indicate a decreased resistance to earth for both the tapered cylinder and the cross shape when compared to the straight cylinder (rod). The effect seems to be considerably less for the 8-in. electrode than for the 15-in. one. Comparing the rod and tapered cylinder data shows that some decrease in resistance to earth apparently results from the increased contact with earth due to the electrode's taper. (The taper produces continuous compacting along its length as described earlier.) The cross-shaped electrodes were made up of 1/4-in. plate steel and were tapered from top to bottom only at the outer edges. The surface area of the cross-shaped electrode was approximately 1.5 times that of the rod cylinder. These electrodes had the lowest resistance to earth of this test group. In the 15-in. long groups the average resistance to earth for the tapered cylinder and cross-shape were 0.88 and 0.87 times that of the rod, respectively. The corresponding values for the 8-in. electrodes were 0.96 and 0.94.

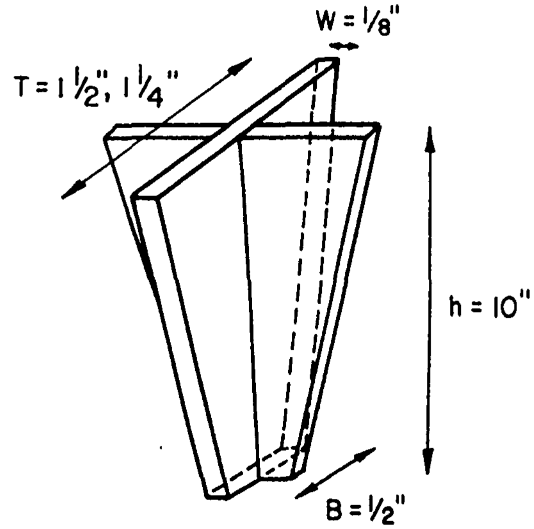
The cross-shaped electrodes in Group 2 had approximately 2.24 times the surface area of the rod used for comparison. The electrodes were constructed of 1/8-in. plate steel. This results in a configuration which has very little overall taper (only on the edges of the vanes). The most significant



Cast bronze four-point star



Straight cylinder



Cross stake

Figure 12. Test group 3 electrodes with dimensions.

Table 6

Volume and Surface Area for Group 3 Electrodes

Group 3 Electrode Type	Volume (cu in.)	Surface Area (sq in.)	Area Ratio (to Cylin.)
Silicon bronze (cast)*	3.98**	42.5**	2.4
Cylinder (9/16 in. diameter)	2.49	17.67	1
Cross stake (1.5 in. diameter)	2.5	40.0	2.5
Cross stake (1.25 in. diameter)	2.19	35.0**	1.98

*Approximate values are used due to complex shape.
**Does not incorporate the volume or area of the 1/2 to 3/4 in. cylindrical metal tops of the stakes.

variable in the Group 2 measurements is therefore the surface area. The measurements indicate that the additional (2.24 times more) surface area in this configuration reduces the resistance to earth--giving an average of 0.79 and 0.86 times that of the rod for the 15-in. and 8-in. electrodes, respectively.

The Group 3 test samples included the rod, two cross-shaped electrodes and a specially cast leaded red brass design. The surface area ratios were approximately 1 : 1.98 : 2.26 : 2.4 in order. The cross electrodes were constructed of 1/8-in. sheet steel as described above and had the outer edges of the vanes tapered. The cast electrode was designed to incorporate a degree of taper in all directions.* This electrode had the lowest resistance to earth of any of the designs tested. All the electrodes in this group were 10 in. long. This length was picked by the sponsor (ADEA) after they examined the results of the theoretical analysis and early test results with the 8-in. and 15-in. electrodes.

It may be noted that the resistance to earth measured for the 1.25-in. diameter cross electrode was consistently less than that for the 1.5-in. diameter cross in the Group 3 tests. It was not determined why this was observed. The 1.25-in. electrode was slightly longer than the 1.5-in. one and was constructed using a spot brazing technique. The 1.5 in. electrode was continuously welded at the crossing joint.

*The cast electrodes were provided under contract by James L. Leach, Professor of Mechanical and Industrial Engineering, University of Illinois, retired. Professor Leach owns a small private metal casting operation.

Table 7

Resistance to Earth Measurements--Individual Electrodes

Type	Resistance (Ohms) Test Numbers I	II	III	IV	V	VI	VII	VIII	IX	X	Ave.	% of Cylinder Resistance
Group 1												
15" Straight Cylinder	86.4	70.8	78.1	---	---	---	---	---	---	---	78.4	100
Taper Cylinder	65.5	67.5	73.8	---	---	---	---	---	---	---	68.4	88
Cross Shape	68.6	66.7	70.4	---	---	---	---	---	---	---	68.6	87
8" Straight Cylinder	143.0	115.0	140.0	---	---	---	---	---	---	---	132.6	100
Taper Cylinder	133.0	120.0	130.0	---	---	---	---	---	---	---	127.7	96
Cross Shape	135.0	116.0	124.0	---	---	---	---	---	---	---	125.0	94
Group 2												
15" Straight Cylinder	94.2	89.4	89.7	---	---	---	---	---	---	---	91.1	100
Cross Shape	76.6	70.1	70.0	---	---	---	---	---	---	---	72.2	79
8" Straight Cylinder	196.0	131.0	149.0	---	---	---	---	---	---	---	158.7	100
Cross Shape	163.0	113.0	131.0	---	---	---	---	---	---	---	135.7	86
Group 3												
10" 9/16" Cylinder	98.3	97.4	104.0	79.1	83.6	63.4	81.3	79.0	79.0	64.9	83.0	100
1.25" Cross	81.9	88.9	85.7	72.1	66.1	53.4	61.4	63.0	67.0	51.9	69.0	83
1.5" Cross	84.1	89.8	81.9	74.4	67.4	60.7	59.4	64.9	76.1	53.6	71.2	86
Red Brass	80.3	74.3	78.7	72.5	66.1	53.7	57.9	55.8	71.7	51.5	66.2	80

Although the data is relatively limited, it will in general support the following conclusions related to the effects of electrode shape on resistance to earth:

1. Tapering the electrode reduces resistance values, compared with a straight cylinder of equal volume, length, and surface area.

2. An increase in surface area, for equal electrode length, also results in a significant decrease in resistance to earth.

The data in Table 7 were statistically analyzed using the one way analysis of variance and students t-test. The confidence level was 90 percent (i.e., if a statistical significance is found, there is 90 percent confidence that the difference exists). Results for each group were:

Group 1: 15 in. length: the cross shape type's average resistance is significantly lower than that for the straight cylinder. The average resistance for the tapered cylinder is not significantly less than that of the straight cylinder (note the large spread in the tapered cylinder's data).

Group 2: 15 in. length: the cross shape average resistance is significantly lower than that of the straight cylinder; for the 8 in. length, there is no statistically significant difference between the average resistances (note the large variability in the data for each type).

Group 3: the cylinder's average resistance is significantly higher than that for each of the other three types. There are no differences among the 1.25 in., 1.5 in., and red brass types' average resistances.

The cast electrode design, which incorporated taper on the surfaces in contact with the soil and had increased surface area as well, provided the lowest resistance to earth in these tests.

Multiple Electrode System Tests

The electrode design chosen for use in a multiple electrode system for the initial comparison with the system HEL provided (26 electrodes, each 8.5 in. long and 9/16-in. in diameter) was the 1/8-in. plate cross-shaped stake (similar to those used in the Group 2 individual electrode tests reported above). Each electrode is 10 in. long, with a surface area of 2 times that of a 9/16-in. diameter straight cylinder. Since the HEL electrodes were slightly shorter, the cross stakes have 2.23 times the surface area of the HEL system electrodes. The volumes (weights) of the cross stakes and the HEL cylindrical electrodes are almost equal.

The cross-shaped stake design was used for this test because it gave the lowest resistance to earth values in the individual electrode tests, compared with the straight and tapered cylinder designs, and the electrode is relatively easy to produce in a machine shop. A 1/8-in. plate thickness was used instead of 1/4 in. because this reduced the individual electrode weight by almost one-half. The lower electrode weight was felt to be more important than the fact that the 1/8-in. plate cross design gave a slightly larger resistance to earth than the 1/4 in. plate design in individual electrode tests.

The grounding system used for this test consisted of 15 1/8-in. thick, 10-in. long cross-shaped stakes strung on a 65-ft, 1/8-in. stainless-steel wire rope. Fifteen electrodes were used because calculations showed this number would give approximately the same total resistance to earth as the 26 HEL electrodes. This system was compared with either 15 or 26 of HEL's electrodes (9/16-in. diameter, 8.5-in. long straight cylinders) driven into the soil in a circle of with the same diameter as used for the USACERL system. Both systems were tested several times according to the "fall of potential" method described previously.

An additional series of tests was conducted after 15 of the cast red brass electrodes were delivered. These tests included measuring the resistance to earth of the HEL system using 15 electrodes, the cross-shaped electrode system (15 electrodes), a system using 15 cast electrodes, and a standard 6-ft long, 3/4-in. diameter galvanized steel ground rod.

Data for the multiple electrode system tests are listed in Table 8. Test V was conducted at a later date with a drier soil than tests I through IV.

Analysis of Data: Multiple Electrodes

In general, the systems with larger surface area electrodes had a lower resistance to ground than did the cylindrical electrode system using 15 electrodes. The lowest resistance in Tests I through IV was measured with the 26 electrode system. The difference in resistance values between the 26 and 15 cylindrical electrode systems for these tests was fairly consistent, averaging 3.09 ohms. The lowest resistance to earth in Test V was obtained from the system with the cast electrodes, which incorporate both an increased surface area (compared to the cylindrical electrode) and tapered surfaces along the length of the electrode.

Thus, the apparent resistance to ground advantage observed with the individual electrodes with these characteristics is also present in a multielectrode system.

The data in Table 8 were compared statistically with the following results:

The average resistance for the HEL(26) type was significantly lower than that for each of the HEL(15) and CERL(15) types. There is no difference between the average resistances of the HEL(15) and CERL(15) types.

Table 8

Resistance to Earth Measurements--Multiple Electrodes

Test Number	HEL (26)* (ohms)	HEL (15) (ohms)	CERL (15)** (ohms)	Cast (15)*** (ohms)	Steel Rod (ohms)
I	7.35	10.4	8.55		
II	6.70	9.60	9.60		
III	7.39	10.5	9.13		
IV	7.12	10.4	8.95		
V	---	15.9	12.9	11.3	21.6

*8.5-in. cylindrical electrode system developed by HEL.
**15 10-in. cross-shaped stake electrode system developed by USACERL.
***Experimental 15-electrode cast silicon bronze system made at USACERL.

5 OPTIMAL ELECTRODE DESIGN

Significant factors to be considered for optimization of the surface wire grounding system include reducing the number of electrodes to a reasonable minimum and using the shortest practical electrode length. This will reduce system weight and facilitate installation. The analytical and experimental studies conducted at USACERL support the premise that the resistance to earth of a ground electrode is inversely proportional to the surface area of the electrode in contact with the soil. Therefore USACERL recommends that the shape of the ground electrode be such that its surface area is significantly larger than that of a rod or cylinder. The recommended geometry is a modified star cross-section designed with a slight taper on all surfaces in contact with the soil. A drawing of this design is given in Figure 13. The length of 10 in. is a compromise among a number of factors, the most important among them being the ease of installation and retrieval. Lengths longer than 10 in. require considerable additional effort to install. The analysis of predicted resistance to ground based on the information plotted in Figures 2 and 3 was also considered in determining the recommended length. Considering a system consisting of fifteen 10-in. electrodes, an 8-in. length would require four additional electrodes to maintain a particular resistance to ground, while an increase to 12-in. is associated with a decrease of two electrodes.

The 3/8-in., cylindrical top on the recommended electrode design is intended to provide a driving surface and to minimize impact damage to the electrode as it is driven into the soil. The four-point modified star design combines a relatively large surface area for contact with the soil with favorable structural characteristics. (The Appendix presents some of the pertinent structural considerations by comparing a cylinder geometry with a cross shape [somewhat related to the recommended star shape].) The recommended diameter of the electrode is 1.25 in. This value was chosen rather than the slightly larger (1.5 in.) dimension of the cast electrodes described in this study. The reason for this difference is the lower weight associated with the smaller diameter. The taper shown on the drawings is a compromise between structural considerations (maximum cross section along the entire vertical dimension) and the desire for adequate taper along the vertical dimension.

The material used for the cast test samples used in this study was leaded red brass. The reason for the choice of this material was that it was readily available locally at a reasonable cost. ADEA performed a durability test on their prototype cast electrodes in February 1988 at Fort Lewis, WA. The electrodes were repeatedly driven into and removed from earth which was a soil-gravel-rock mixture. They concluded that the brass electrode's expected lifetime in these extremely hard conditions was 90 to 100 uses.

Ten star-shaped electrodes consisting of cast stainless steel (HE-60, 28Cr-10Ni, poured by Alloy Casting of Champaign, IL) were received late in this study. No test were conducted with these, but the material appears to be much harder and more durable than the brass used for the test systems. Pertinent factors to be considered related to the option of stainless steel electrodes include:

a. probable slightly higher material cost,

b. should be no corrosion problems,

c. longer lasting than the brass, and

d. compatible with readily available stainless steel wire rope.

Another option not studied, but which may be practical, is the use of nodular or malleable iron for the electrode castings. These would need to be galvanized and could be used with galvanized wire rope

(the lowest cost wire rope material). All electrodes cast for this study were made using a "green molding sand process" with the pattern vertical.

The cost of manufacturing by forging has been estimated by various sources* to be five to seven times that of casting.

A cost analysis was not part of this study; however, a considerable cost savings over an extended period of time appears to be one of the major advantages of the new system. The contractor who supplied the cast electrodes for this study estimated a manufacturing cost of $6 to $7 each for similar electrodes in small quantities. This results in an electrode cost of $90 to $105 for 15 electrodes. He stated that the cost of stainless steel would be approximately twice that of the brass. The procurement cost for the 6-ft rod is $40 each. According to ADEA, these rods are used an average of three times, resulting in a cost of approximately $13 per use. (In some tactical exercises, no effort is made to retrieve the electrodes, thus they are used only once.) Therefore the cost of 15 electrodes would be covered in 7 to 8 uses of the 6-ft rod. With a lifetime of 90 to 100 uses, the new electrodes would save many times their cost.

*James L. Leach, Professor of Mechanical and Industrial Engineering, University of Illinois, retired, and the U.S. Army Computer and Electronics Command (CECOM).

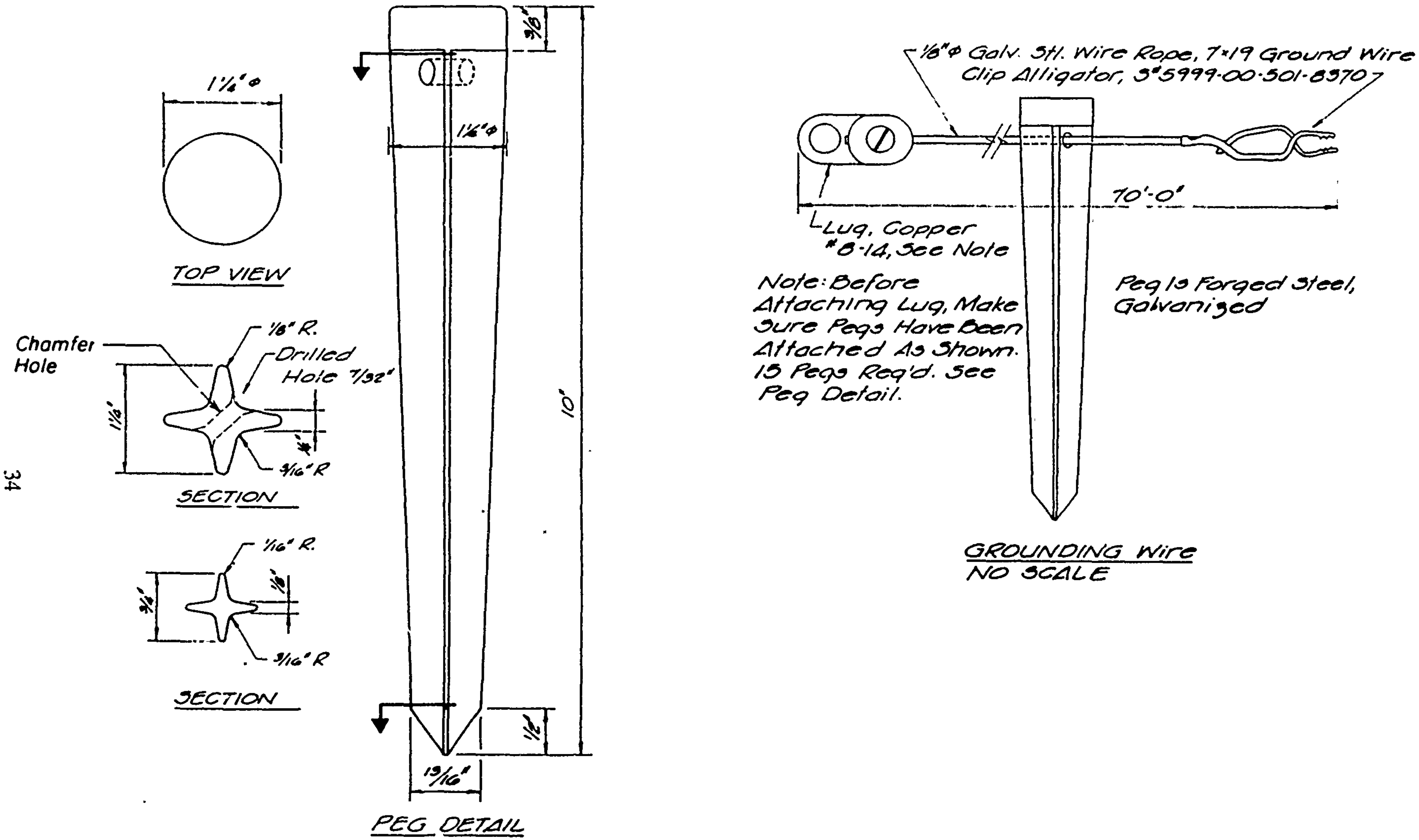


Figure 13. Surface wire ground system electrode and cable.

6 WIRE ROPE CONSIDERATIONS

A number of different wire ropes (sizes and materials) were ordered for visual examination and observation of characteristics such as strength, flexibility, electro-chemical compatibility with electrode materials, and experimental use. Pertinent characteristics of a number of wire ropes are listed in Table 9 along with costs as listed in McMaster-Carr Catalog 93.*

A number of factors need to be considered in relation to the diameter of the wire rope used. High currents associated with lightning grounding, strength and durability all favor larger diameters. Lower cost and portability are associated with smaller diameters. The diameter of the wire rope used for the USACERL experimental systems was 1/8 in. (the lowest cost and least weight). It appears that most of the advantages of the smaller diameter could be retained with a 3/16 in. diameter. The large diameter would be more likely to survive lightning.

The electrical contact between the wire rope and the grounding electrode is essentially a surface contact between the wire rope and the inside of the hole for it in the electrode. The electrodes are typically slid along the wire rope whenever the system is installed or taken up for storage. This should tend to remove surface oxides, dirt, or other contaminants from the mating surfaces. If the electrode is installed with its top flush with the surface of the ground and with the wire taut, the wire will be forced against the stake surface in the hole. Good electrical contact should be present if both metal surfaces are clean. However, an electrical potential leading to corrosion can exist if the wire rope is of a different metal than the electrode. Corrosion can be a problem for dissimilar metals in a damp environment even for a relatively short time. An experiment was conducted to measure the voltage developed between a short section of stainless steel cable and galvanized steel (a pipe elbow). The two items were placed into wet earth and the voltage between them was measured with a Fluke Model 77 Digital Voltmeter. The measured voltage was 0.5 V. Although a corrosion potential analysis (corrosion rates versus time, moisture, and soil parameters) was not part of this study, it appears to the authors that this voltage difference makes this combination of metals undesirable for this application. On the other hand, the nature of tactical operations is such that the grounding system typically will be installed in any one location only for a limited period (a few hours). Thus, in most cases, the time available for corrosion to take place will be relatively limited.

The wire rope ends should be treated to prevent unraveling and fraying. This would expedite cable replacement and help prevent puncture wounds from the fine wire ends. Ideally, such a treatment should not increase the diameter of the cable, thus should not require a larger hole in the electrode. One technique which was reasonably successful in the laboratory was to wrap 1 to 2 turns of glass cloth electrical type (Scotch No. 27) tightly over the wire rope and cut the rope in the middle of the tape. The cable seems to be the weakest part of the design, and if it is readily replaceable, the system can be built to last indefinitely.

USACERL recommends using a No. 8 to 14 copper lug for the reel end of the wire rope cable. This will allow easy attachment and removal of the cable from the reel and provides a means for terminating the cable without having lots of fine steel wires pointing in many directions. The lugs are readily available from electrical supply outlets.

The proposed configuration for the surface wire grounding system (Figure 1) includes connections between each of the four corners of the vehicle to the encircling ground wire. A quick disconnect securely mounted to each corner of the vehicle would expedite installation and retrieval of the system.

*McMaster-Carr Supply Company, P.O. Box 4355, Chicago, IL 60680-4355.

Table 9

Wire Rope Characteristics

Type	Diameter (in.)	Breaking Strength (lb.)	Relative Flexibility*	Cost per ft*
Stainless steel Type 305, 7 by 19**	1/8	1300	Good	$1.25
Stainless Steel, Type 302, 6 by 42	1/8	700	Excellent (most flexible steel)	$1.34
Stainless Steel, 7 by 19***	1/8	1760	Excellent	$1.13
Stainless Steel, 7 by 19***	5/32	2400	Excellent	$1.16
Stainless Steel, Type 302, 6 by 42	3/16	3700	Excellent	$1.26
Galvanized Steel, 7 by 19	1/8	2000	Very good	$0.32
Galvanized Steel, 7 by 19	3/16	4200	Very good	$0.41
Phosphor Bronze, 6 by 42	1/8	335	Excellent	$1.46
Phosphor Bronze, 6 by 42	3/16	760	Excellent	$1.69
Phosphor Bronze, 7 by 19	1/8	615	Very good	$1.04

*As listed in McMaster Carr Catalog 93, 1987.
**The first number indicates the number of strands and the second number specifies the approximate number of individual wires in each strand. The wire rope may be available with a fiber core or an independent wire rope core.
***Local procurement, Type unknown, but most likely Type 302.

7 REEL DESIGN

HEL's system used a modified hand-operated boat trailer winch as the reel to wind and store the wire rope. This reel worked fairly well, but the USACERL users felt that it could be improved somewhat by central placement of the handle and a larger center diameter of the spool center on which the rope is wound. The drawings furnished by HEL showed that these changes had already been incorporated. USACERL experimented with several brands of boat trailer winch reels and with other designs. The final design which USACERL recommends is shown in Figures 14 to 16. A photograph of the reel provided by HEL and the USACERL design is shown as Figure 17. It incorporates a trigger-operated stop. The stop is desirable because the person taking up the system will most likely first pull on the reel to dislodge the electrodes from the ground as the cable is wound onto the reel. If there is no stop, one hand must hold the crank and the amount of force that can be applied to the system is limited. The crank will tend to be forced backward. With a stop or lock, both hands can be placed on the handle and significantly more force can be applied to dislodge the electrode. The HEL prototype has a spring loaded stop which can be set in the locked position while the cable is being wound. While this is a convenience to the operator, an associated disadvantage is that operation in this state generates considerable noise, which may be undesirable in a training or deployed situation.

The length of the pin through the spool and the crank mechanism on the USACERL design is such that the copper lug attached to the end of the wire rope cable can be attached to it. The use of cotter pins expedites replacement of the cable and electrode system if necessary.

The prototype reel was constructed of steel; however, aluminum or high strength aluminum alloy could be used if saving weight is necessary.

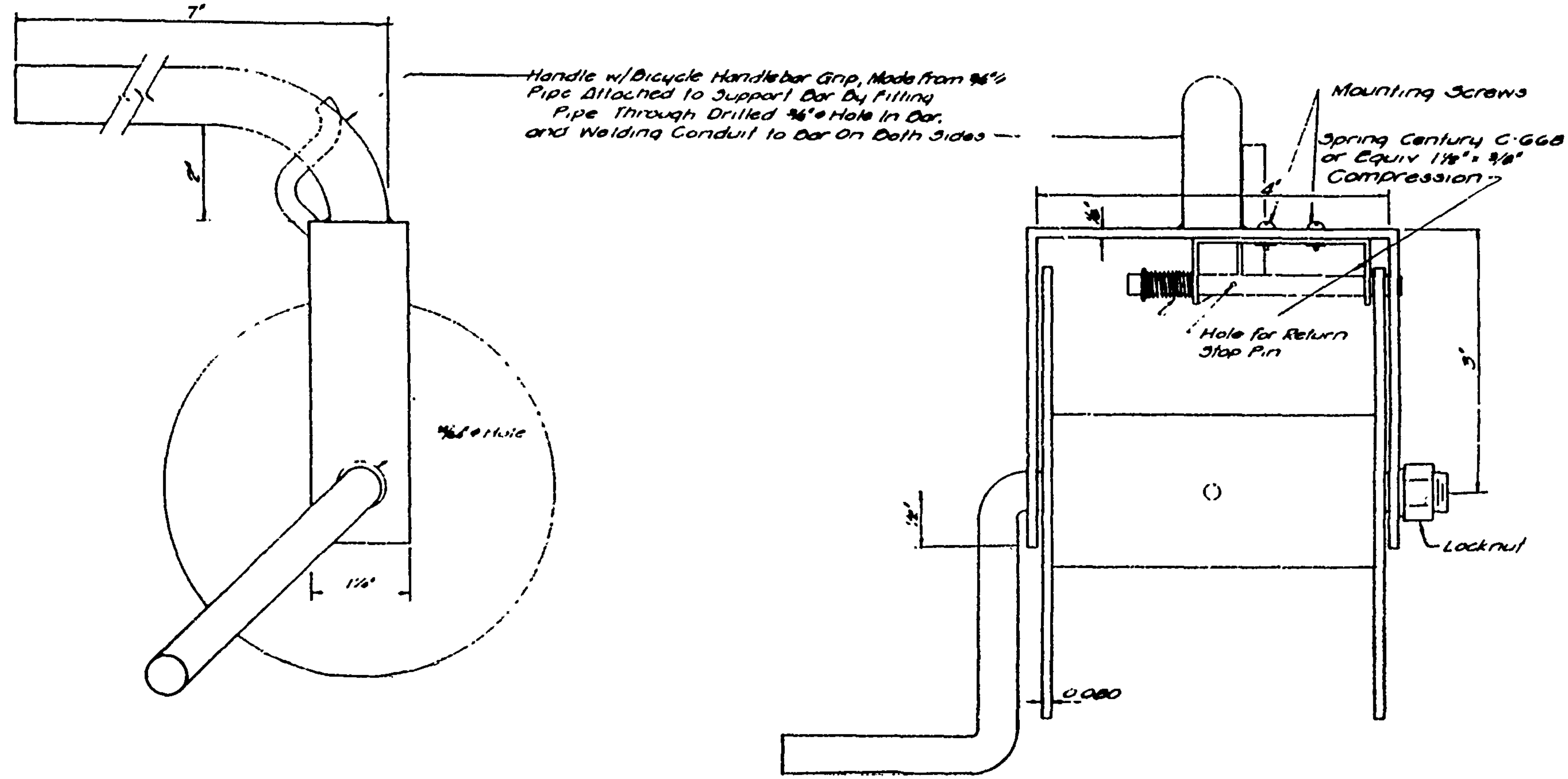


Figure 14. Surface wire ground system reel-assembled.

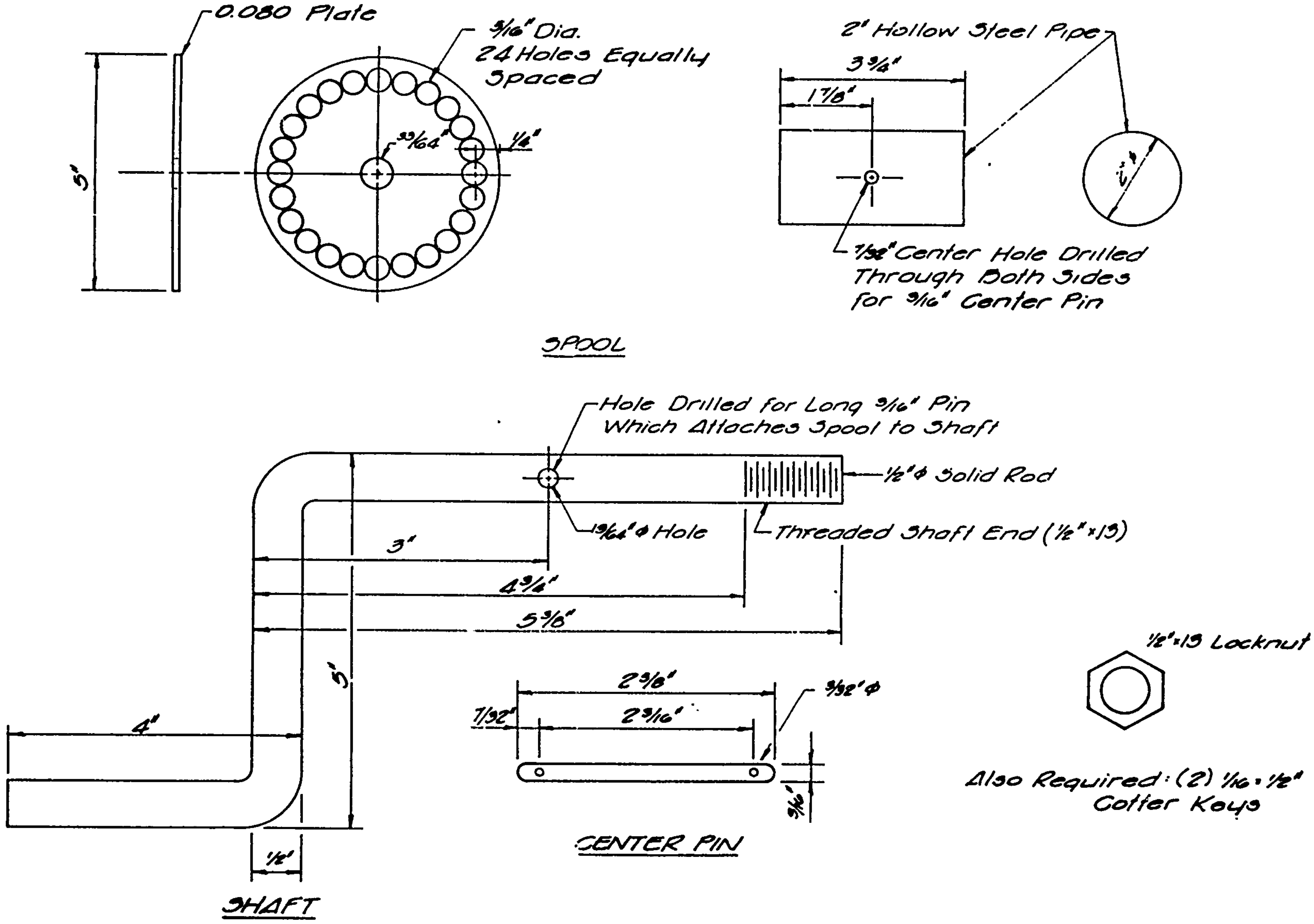


Figure 15. Surface wire ground system reel--parts details.

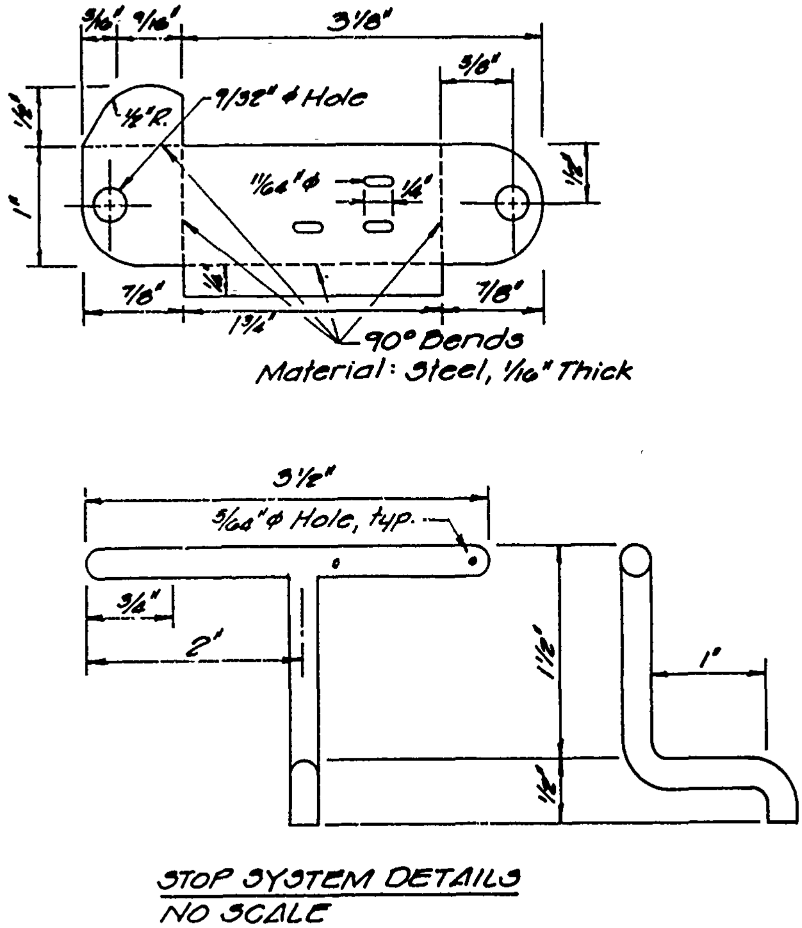


Figure 16. Surface wire ground system reel--stop system details.

Figure 17. HEL-supplied and USACERL-designed reels.

8 CONCLUSIONS

The goal of this study was to optimize several parameters associated with a proposed concept--the surface wire grounding system--for grounding tactical systems such as shelters transported on tactical vehicles or Standardized Integrated Command Posts. This system as presented to USACERL consisted of 26 cylindrical electrodes (each approximately 10 in. long) strung on a 100 ft wire rope cable. However, a number drawbacks (such as weight, handling and installation difficulties, and high procurement cost) suggested reducing the number of electrodes and limiting their length. The theoretical and experimental studies described in this report showed that an electrode's resistance to earth is inversely proportional to the surface area in contact with the soil. Thus, an electrode configuration with a relatively large surface area and a taper on all surfaces in contact with the soil appears effective in decreasing the number and/or length of grounding electrodes while maintaining a constant resistance to earth. The taper design is desirable in that it tends to maintain continuous contact with the soil along the vertical axis of the electrode as it is driven into the ground.

A design consisting of a modified four-point star cross section shape (10 in. long) incorporating these features was made and tested with satisfactory results. The USACERL test electrodes were cast leaded red brass; however, galvanized or stainless cast steel may be more cost-effective and durable materials. Fifteen of the red brass electrodes (with approximate one-pace spacings) on a 70-ft cable installed in a circle provided significantly less resistance to earth than a single 6-ft electrode. The tested design had adequate strength to allow the user to remove the electrodes from the earth by pulling with both hands on the unit. A trigger operated locking device aided this process.

Desirable characteristics for the surface wire are flexibility, strength, and corrosion compatibility with the electrode material. Galvanized steel wire rope with a nominal diameter of 3/16 in. appears to be the most satisfactory material to use with galvanized steel electrodes, but it appears to be electrochemically incompatible with the red brass electrodes. The optimum approach appears to be cast stainless steel electrodes with a 3/16 in. stainless steel wire rope. The cost will probably be slightly higher than brass or galvanized steel, but durability should be greater and corrosion problems eliminated.

The takeup reel for the surface wire was redesigned. The new design's features include silent operation, a trigger-operated stop, lighter weight, and provisions for rapid change of cable.

9 RECOMMENDATIONS

Based on the results of this study the following features and dimensions are recommended for a surface wire grounding system:

Number of electrodes	15 to 18
Electrode length	10 in.
Electrode design	Tapered four-point star, as shown in Figure 14.
Electrode material	Cast steel, hot-dipped galvanized after holes are drilled for cable (or stainless steel)
Electrode spacing	Approximately 1 pace
Wire rope length	65 to 70 ft
Wire rope size	1/8-in. diameter, 7 by 19
Wire rope material	Galvanized steel (or stainless steel for stainless steel electrodes)
Reel design	Silent, trigger-operated locking mechanism; strong enough to be used to dislodge electrodes; cotter-pin assembly. Design as in Figures 15 to 17.

A lower number of electrodes (15) has the advantage of being slightly easier to use and probably would provide an adequate ground connection, but a higher number might be justified to allow for possible breakage.

The material used for the prototype systems supplied to ADEA was leaded red brass (Cu-5%Sn-5%Pb-5%Zn). This material was used because it was available locally. In addition, the supplier indicates that this material should perform satisfactorily for this application. However, steel is preferred for both electrodes and rope, as noted above, for durability and cost considerations. If the brass is used, the authors recommend 1/8-in., or 3/16-in. 7 by 19 phosphor bronze wire rope. Phospher bronze wire rope is readily available and is electrochemically compatible with red brass; however, the breaking strength of this rope is not very high.

Although the existing data indicate that a satisfactory electrical contact to the earth can be obtained with the surface wire ground system as tested, additional comparison testing with a variety of grounding conditions is desirable. The system has great advantages in ease of installation and retrieval and appears to provide greater safety during lightning conditions than existing practices. Therefore, the authors recommend its fielding for tactical operations. In addition, the system has been developed to the state where type certification is recommended.

APPENDIX:

MECHANICAL EVALUATION OF ELECTRODE DESIGN

A mechanical evaluation of the proposed electrode design was needed to estimate the structural integrity of the electrode while in use. Certainly limits must be placed on minimum electrode dimensions for it to retain the required strength to satisfactorily survive the impact stresses to which it will be subjected. An electrode being driven into the ground may hit a rock or other hard surface, which may bend or fracture it. The design used as a basis for comparison was a 9/16-in. diameter straight cylinder (rod), the design used for the HEL system. This system with an 8.5-in. rod had already been used under a variety of soil conditions before USACERL became involved in this study, and with the exception of some tests conducted in arctic permafrost, has held up fairly well.

For this analysis a cross-shaped electrode design was examined to determine limiting dimensions that would have the equivalent structural strength of the 9/16-in. diameter straight cylinder.

The strength of a structural member undergoing bending stress is determined by the section modulus, S, of a cross section of that member. The section modulus is equal to the moment of inertia, I, divided by the maximum difference dimension from the neutral axis, C, or S = I/C.

To determine the section modulus, S, of the straight cylinder, consider its circular cross section (Figure A1). The section modulus of a circular cross section is given by:

$$S = \frac{I}{C} = \frac{(1/4)\pi r^4}{r} = \frac{\pi r^3}{4} \qquad \text{[Eq A1]}$$

Here, for a 9/16-in. diameter rod, S = 0.0175 cu in.

Consider the cross stake with minimum plate thickness of 1/8 in. The cross-sectional view is shown in Figure A2. For this shape:

$$I = \frac{bh^3}{12} = \frac{(1/8)h^3}{12} + \frac{(h-1/8)\,(1/8)^3}{12} \qquad \text{[Eq A2]}$$

and

$$C = \frac{h}{2} \qquad \text{[Eq A3]}$$

Its section modulus is given by:

$$S = \frac{I}{C} = \frac{h^3/8 + h/512 - 1/4096}{6h} \qquad \text{[Eq A4]}$$

A thickness of 1/8 in. yields a cross stake width, h, of 0.9091 in. for S = 0.0175 (the section modulus of a 9/16-in. circular cross section). Increasing the thickness from 1/8 in. to 3/16 in., decreases the cross stake width h to 0.73 in. for the same section modulus.

A taper from the top to bottom is a desirable feature for electrodes for the surface wire grounding system. The cross stake was designed with h to be the largest at the top, (1.25 in.) tapering to a smaller dimension at the bottom. The section modulus is thus a maximum at the top and a minimum at the bottom. This means that the bottom of the stake is the weakest. Thus if h is 0.91 in. at the bottom, for a plate thickness of 1/8 in., the cross stake will have a greater strength along its entire length than a 9/16 in. cylinder.

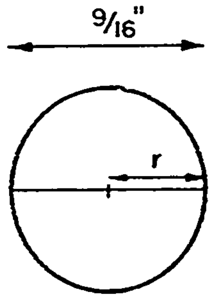


Figure A1. Cross-sectional view of 9/16-in.-diameter straight cylinder electrode.

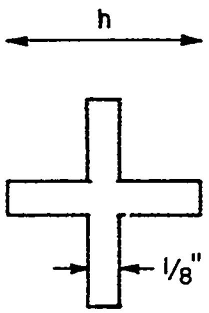


Figure A2. Cross-sectional view of 1/8-in.-plate cross electrode.

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